ANAEROBIC DIGESTION OF THE LIQUID FRACTION OF DAIRY MANURE IN PILOT PLANT FOR BIOGAS PRODUCTION: RESIDUAL METHANE YIELD OF DIGESTATE

Carlos Rico[a*], José Luis Rico[b], Iñaki Tejero[a], Noelia Muñoz[b] and Beatriz Gómez[b]

[a] Department of Sciences and Techniques of Water and Environment, University of Cantabria. Los Castros s/n, 39005 Santander, Spain.

[b] Department of Chemical Engineering and Inorganic Chemistry, University of Cantabria. Los Castros s/n, 39005 Santander, Spain.

*****Corresponding author. Tel.: +34-942201848; fax: +34-942201703

E-mail address: ricoc@unican.es

Abstract

The performance of the only dairy manure biogas plant in Cantabria (Northern coast of Spain) was evaluated in terms of liquid-solid separation and anaerobic digestion of the liquid fraction. Screened liquid fraction was satisfactorily treated in a CSTR digester at HRTs from 20 to 10 days with organic loading rates ranging from 2.0 to 4.5 Kg VS/(m^3·d). Stable biogas productions from 0.66 to 1.47 m^3/(m^3·d) were achieved. Four anaerobic effluents collected from the digester at different HRTs were analysed to measure their residual methane potentials, which ranged from 12.7 to 102.4 L/g VS. These methane potentials were highly influenced by the feed quality and HRT of the previous CSTR anaerobic digestion process. Biomethanization of the screened liquid fraction of dairy manure from intensive farming has the potential to provide up to 2% of total electrical power in the region of Cantabria.

Keywords: Biogas; Pilot plant; Anaerobic digestion; Dairy manure; Screw press; Digestate.

1. Introduction

One of the new trends of dairy farming in Spain is to intensify the animal production, which is always accompanied by the production of large amounts of manure, not properly managed by farmers, presenting a considerable environmental threat in these zones. In humid areas, particularly where the ground shows pronounced slopes, the liquid fraction of dairy manure is the most problematic due to run-off and lack of sufficient land for disposal, resulting in a surplus of nitrogen in the areas where intensive farming is concentrated. One such region is that of Cantabria, located in Northern Spain, which has a bovine population of around 280,000 livestock units (mainly milk).

Anaerobic digestion of dairy manure has been demonstrated to be an attractive treatment that provides several benefits including the improvement of manure fertilizer quality; reduction of odours, pathogens and greenhouse gas emissions; and production of a renewable fuel, the biogas (Albertson et al., 2006; Chae et al., 2008; Hartmann and Ahring, 2005; Hawkes et al., 1984; Kaparaju and Rintala, 2003).

Dairy manure composition depends on the cows' diet and the conditions under which animals (dairy cows, breeding cows, and calves) are kept in the farm. In addition to solid and liquid dejections, dairy waste extracted from cow houses contains the remains of food and bedding (straw, sand, sawdust, etc.). Many of these solids are recalcitrant or barely biodegradable (Rico et al., 2007). Separation of liquid and solid fractions of manure is a desirable upstream operation in the treatment process since dewatering the solid fraction lowers the cost of shipping, which facilitates the export of nutrients from the areas with excess of manure and the redistribution of these nutrients to other areas in need of them (Holm-Nielsen et al., 2009). Before its transport, the solid fraction can be subjected to dry anaerobic digestion and/or the composting process which would represent an additional reserve of more stable organic carbon and nitrogen for the cultivated soil (Atallah et al., 1995).

Moreover, the separated liquid fraction, which has much less suspended solids content, would be more easily subjected to an anaerobic process requiring a simpler reactor as well as lower temperature and hydraulic retention time (HRT) than those conditions for unscreened dairy manure (Liao et al., 1984). The digested liquid fraction can be used as a fertilizer for agriculture (Morris and Lathwell, 2004; Mantovi et al., 2010). In addition, it would be favourable to further refine the liquid fraction into concentrated fertilizers or to receive post-treatments to obtain clean water, suitable for recycling (Holm-Nielsen et al., 2009).

Separation of dairy manure can be performed before or after anaerobic digestion. The main advantage of separation before digestion is the removal of the fibrous part, which can cause clogging problems within the reactor and pipelines (Wen et al., 2007). In addition, fibrous materials hinder pumping and mixing. However, about half of VS remains in the solid fraction (Møller et al., 2002) which implies a lower amount of recoverable energy. One way to harness this potential energy contained in the solid fraction is through the dry anaerobic digestion process, which is usually performed discontinuously without any mixing of the solid substrate (Weiland, 2006).

Anaerobic digestion in CSTR reactors has been widely studied by several researchers with different manures at both the lab scale (Boe and Angelidaki, 2009; Hawkes et al., 1984; Liao et al., 1984; Lo et al., 1983; Karim et al., 2005; Zeeman et al., 1988) and the pilot scale (Kaparaju et al., 2008). However the majority of these works utilize the lab scale in which manure is conserved at low temperatures or even frozen prior to its use to prevent degradation of the feed. Also there is a lack of information about pilot CSTR installations processing the liquid fraction of dairy manure by employing industrial or semi-industrial equipment.

In this work, the performances of the screw press separator and the 1.5 m^3 CSTR anaerobic digester of the only dairy manure biogas plant in Cantabria, a pilot plant located in the Agrarian Secondary School “La Granja” (Heras, Cantabria), were tested. The CSTR reactor was fed with the screened liquid fraction of dairy manure in mesophilic conditions. Residual methane production from the pilot plant screened/digested liquid fraction was also measured at the lab scale.

2. Materials and Methods

2.1. Pilot plant

The pilot plant was projected for 2008 and inaugurated in June 2009. During the realization of the present work, a screw press separator (Doda MS5CE, 0.8 mm mesh) and a CSTR digester were employed as the main components of the installation. Figure 1 shows the scheme of the installation and technical parameters of the components used in the pilot plant tests.

A chopper centrifugal pump (Cri-man, ETO series) was used to recirculate the raw manure slurry, avoiding stratifications, into the storage tanks and to pump the slurry to the separator. Two mono pumps (Seepex, BN-025-12 and BN-2-6L) were employed for feeding the reactor and recirculation of the reactor content.

The CSTR digester consisted of a cylindrical fixed dome vessel made of 304 stainless steel and was equipped with temperature and pH probes. Inside, the digester is covered with epoxy painting and the exterior wall is thermally insulated to prevent heat loss. The reactor has two sampling ports, one in the effluent tube and the other in the recirculation pipe, as well as a purge valve in the bottom to remove sinking materials. Mixing is accomplished by recirculation of reactor content. Recirculation was also used to maintain the temperature of the process since the recirculation pipe passes through a heat exchanger. Water was used as heating fluid and was heated up to 55ºC in a 500-L electric heat accumulator tank. The heat exchanger (HRS Spiratube) consisted of a corrugated tube within a tube.

Biogas left the reactor by its own pressure and was measured using a mass flow meter (Bronkhorst, F111-BI). Biogas passed through a catch pot and a coalescing filter to protect the biogas meter from condensates and particulate matter. A sampling port was installed between the coalescence filter and the mass flow meter. At the end of the line biogas was burned in a flare (Emison, A-5 ESP).

The control panel was located in a closed, protective box. This panel contained all the electric system controls required for the functioning of the pilot plant. The heating system was commanded by the temperature probe to maintain the temperature of the digester at 37±1ºC.

In addition to the equipment described above, the pilot plant also had a decanter centrifuge to refine the digested screened liquid fraction in a nutrient-rich solid fraction and a liquid fraction free of suspended solids in addition to a UASB reactor for implementing the process performed by García et al. (2008) at lab scale. In addition, the pilot plant had facilities for recovering nutrients from anaerobic liquid effluents by struvite precipitation and other post-treatments to obtain a final liquid effluent suitable for reutilization. The performance of these processes was not considered in the present work.

2.2. Mode of operation

The CSTR reactor was filled with screened manure in September 2009 and the heating system was programmed to slowly obtain the operation temperature, achieved after three days. The recirculation pump then was programmed to work eight times per day for 30-minute cycles at a flow rate of 1000 L/h to keep the reactor content well mixed. In addition, the recirculation pump was programmed together with the heat exchanging system to automatically start when the temperature controller detected the need for heating to maintain a stable reactor temperature of 37±1ºC.

The reactor was not fed again to allow for the growth and acclimatization of methanogenic biomass and organic matter stabilization of the reactor content. After 35 days, analysis of the reactor content showed that volatile fatty acids (VFA) had been totally removed. The reactor then was started up at an HRT of 20 days and fed in a semi-continuous mode in 30-minute cycles. Feeding cycles were equally distributed throughout the day and the recirculation pump was programmed to work at the same time as the feeding pump to enhance mixing. Feeding cycle data are presented in Table 1. 75 litres of reactor content were purged weekly from the bottom of the reactor to remove inorganic and sinking materials that enter the reactor with the feed (e.g. sand) or are formed during the process.

2.3. Manure characteristics

Dairy manure was collected from the dung pit of a near 500-free stall dairy cow farm equipped with scrape systems. The diet of the dairy cows was a constant during the experimental period. Manure was extracted from the dung pit by a tractor equipped with a vacuum tank system and then transported and discharged into the raw manure tanks of the pilot plant. Because manure remained stored in the raw manure tanks during the pilot scale experiments, the effect of manure storage time on biogas production could be observed. The characteristics of raw manure are reported in Table 2.

2.3.1. CSTR feed preparation

Dairy manure was screened by the screw press separator. The feeding tank received the screened liquid fraction for feeding the CSTR reactor. The feeding tank was filled up and when it became empty, it was cleaned with a vacuum cleaner to remove sediments from the bottom and filled again. The solid fraction was collected in a 400-L container and composted. However, composting of the solid fraction was not under consideration in this study.

2.4. Residual methane tests

Digestate samples were collected at the exit of the CSTR in 5-L containers for transport to the lab. Batch tests were started within two hours of their collection. Tests were performed in 2.5-L PVC reactors and incubated at 35°C in a thermostatic bath for sixty days without stirring. Methane production was measured by means of a displacement system using an alkaline solution to absorb the CO_2 produced. Each trial was performed in duplicate.

2.5. Analytical Techniques

The VFA concentrations of the CSTR influents and effluents were determined using a HP6890 gas chromatograph (GC) fitted with a 2-m · 1/ 8-in glass column, liquid phase 10% AT 1000, packed with the solid-support Chromosorb W-AW 80/100 mesh. Nitrogen was used as the carrier gas at a flow rate of 14 ml/min, and a FID detector was installed. VFA concentrations are expressed in COD units. The volume of biogas generated in the pilot plant CSTR reactor was measured by a mass flow meter and registered by an electronic unit. Biogas composition was assayed on a 2-m Poropak T column in a HP 6890 GC system with helium as the carrier gas at a flow rate of 15 ml/min with a TCD detector. Biogas and methane volumes are expressed at 0ºC and 1 atm. All other analyses, including TS, VS, pH, COD, total Kjeldahl nitrogen (TKN-N), NH_4^+-N and total phosphorus (P_T), were performed according to standard methods

(APHA, 1998). All the analyses were performed in duplicate; the mean values are reported herein.

3. Results and discussion

3.1. Performance of the screw press separator

The screw press produced a screened solid fraction (SSF) and a screened liquid fraction (SLF). The amounts of these fractions were measured twice because large quantities are difficult to handle. A mass balance of the separation process is presented in Table 2.

The screw press separator produced an SSF upon an increase in the concentrations of TS, VS, TKN and P_T of 2.76, 3.11, 1.14 and 1.23 times, respectively. About 18% of the manure mass was found in the solid fraction, implying that 49.8% and 55.9% of the TS and VS were transferred to the solid fraction. Regarding the removal of nutrients, 20.6% and 22.2% of TKN and P_T, respectively, were transferred to the solid fraction. Wu (2007) reported similar recovery percentages in the solid fraction (48.2% for dry matter (DM), 12.5% for P_T, and 22.7% for TKN). However, these values were higher than those found by Møller et al. (2002), who reported values of 29.9-13.1% for TS, 12.7-4.0% for TKN and 15.4-8.0% for P_T in the screw press separation of cattle manure. The lower DM content of manure in that work (63.7-44.9 g/l) could be the reason for this difference. Whereas the SSF-manure ratio in the present work obtained percentages of 18%, Møller et al. (2002) reported only 5.2% and 2.4%. However, Zhang and Westerman (1997) reported that the performance data of mechanical separators vary widely not only because of the different testing and reporting procedures, but also because the characteristics of the manure used are sometimes different. Later tests performed with the screw press separator showed that with a smaller DM content in the manure slurry, a smaller SSF-manure ratio, in terms of the mass and lower removal efficiencies of DM and nutrients, was achieved. Specifically, an SSF-manure ratio of 8% and TS, TKN and P_T removal efficiencies of 33.5%, 12.5% and 14.9% respectively, were obtained when a manure slurry with 53.7 g TS/L was subjected to screw press separation. In the light of these results, nutrient removal was influenced by the solids input concentration: as the solids concentration in the influent increased, the removal of nutrients increased, as reported by Converse et al. (1999). Furthermore, the screw press was especially efficient in removing DM but not nutrients, as reported by Møller et al. (2000, 2002) and Pain et al. (1978) reported. This phenomenon is due to a large proportion of small particles containing nutrients that remain in the liquid fraction after screw press separation.

3.2. Performance of the CSTR pilot reactor

3.2.1. Feed characteristics and removal percentages of COD and VS

Table 3 shows the characteristics of the screened dairy manure employed as feed and the effluent for the four HRT tested. Because the manure came from the uncovered dung pit of a near farm, climatological conditions (especially rain for the HRT 16.7-day feed) affected the characteristics of manure because of dilution with rain water.

The CSTR reactor operation started at an HRT of 20 days with an organic loading rate (OLR) of 2.0 kg VS/(m^3·d). At the last HRT performed (10 days), the OLR applied was

4.5 kg VS/(m^3·d). At the 16.7 days HRT, the CSTR feed (SLF) presented a lower organic load, resulting in a similar OLR for the 20 and 16.7 days HRT. The average steady-state removal percentages of COD_T and VS are shown in Figure 2. For all the HRTs, COD_T and VS reduction were about 37-41% and 30-36%, respectively, showing a similar performance of the reactor when the OLR increased. Generally, when the HRT decreases and the OLR increases, the percentage of COD removed should decrease if the methanogenic activity of the biomass involved in the process was maintained. However, as observed in this work, biomass growth and acclimatizing throughout the experimental period should help in compensating for the increase in the OLR, maintaining the COD removal percentage of the reactor.

Compared with previous works, Lo et al. (1983) reported maximum COD and VS removal rates of 22-24% and 23-27% at HRTs between 8 and 10 days when treating diluted screened dairy manure (4.4% TS, 3.4% VS) at a lab CSTR at 30ºC. Hawkes et al. (1984) reported VS removal percentages of 17%, 33% and 40% at 5, 15 and 18 days HRT on the anaerobic digestion of screened cattle slurry, with a mean VS content of 2.84%, at 35ºC.

3.2.2. Biogas production rates and methane content of biogas

Figure 3 shows daily biogas production rates throughout the experimental period. Whenever raw manure tanks were near empty or a shorter HRT was set, fresh manure was taken from the near farm, which occurred on days 43, 80, 110 and 140.

Depending on the ambient temperature, stored manure in the tanks was more or less rapidly degraded. For this reason, during the last days of operation for each HRT, biogas production suffered pronounced decreases (days 36-43, 70-80 and 130-140) due to the aging of manure. To calculate the average steady state values of biogas production for each HRT, the days of the experiment when biogas production diminished due to feed degradation were not considered.

In Table 4, the mean specific biogas and methane production as well as volumetric biogas and methane production rates are shown. The reactor started to be fed in October at an HRT of 20 days (day 0) and a mean OLR of 2.0 Kg VS/(m^3·d). After eight days, the biogas production reached stable values. The mean biogas production rate for this period was 992 L biogas/d, which represents 327 L biogas/Kg VS and a volumetric biogas production rate of 0.66 m^3/(m^3·d). A peak in biogas production at day 25 (1150 L biogas/d) was observed, which was due to a failure in the Tª probe that increased the temperature of the reactor to 41ºC. At day 43 biogas production was reduced to 596 L/d due to degradation of the feed.

From days 44 to 80, the HRT was set at 16.7 days. Due to heavy rains in the days prior, the SLF presented a lower organic load than that of the SLF processed before at 20 days HRT. This implied that OLR was almost the same (2.1 Kg VS/(m^3·d)) and volumetric biogas production rate was only a bit higher (0.72 m^3/(m^3·d)) than those with the previous HRT. Specific biogas production for this period was 336 L/Kg VS, quite similar to that of the previous period,. The peak in biogas production at day 54 was caused by another failure in the Tª probe. The digester performance remained stable until degradation of the feed caused a slow decrease in biogas production.

With fresh manure, the HRT was set at 12.5 days on day 80. As observed from the data in Table 3, the SLF presented a higher organic load than the SLF processed previously. Due to decreasing HRT and increasing organic load of the SLF, OLR increased by up to 3.5 Kg VS/(m^3·d). Biogas production strongly increased, reaching a mean value of 1816 L/d and a volumetric biogas production rate value of 1.21 m^3/(m^3·d). The better characteristics of the feed also resulted in a higher specific biogas production, 349 L/Kg VS. The fall in biogas production on day 120 was caused by an electrical failure that stopped the recirculation pump, causing a drop in temperature reactor to 29.5ºC. The problem was solved and the system rapidly recovered temperature and performance. In this sense, Chae et al. (2008) reported that although temperature shocks led to a reduction in biogas production, methanogenic bacteria have a considerable ability to adapt to moderate temperature changes.

On day 140, the HRT was set at 10 days. For this experimental period, the combination of the shortest HRT and the best characteristics of the feed in terms of organic load and VFA content resulted in an OLR of 4.5 Kg VS/(m^3·d) and the highest biogas yields. Specific biogas production slightly decreased due to the lower HRT (328 L/Kg VS), but mean biogas production increased to 2210 L/d and volumetric biogas production rate reached the maximum value of the test, 1.47 m^3 biogas/(m^3·d). The reactor showed a stable behaviour, but the presence of VFA in the effluent was observed.

The methane content of biogas throughout the experimental period ranged from 57% to 72% (Figure 4). Under steady state conditions, the methane content of biogas was consistent: 63%, 65%, 63% and 68% for 20, 16.7, 12.5 and 10 days HRT, respectively.

Decreases in methane content were detected when HRT was reduced until steady state conditions were reached. On the other hand, the highest methane content in biogas (72%) was reached between days 121 and123 when the reactor performance was recovering from a drop in temperature. That was probably due to the higher solubility of CO_2 at the lower temperature.

The results obtained in this test showed that the anaerobic digestion of the screened liquid fraction of dairy manure at 37ºC permits stable operation with HRTs as short as 10 days (OLR 4.5 Kg VS/(m^3·d)) and the obtainment biogas and methane volumetric production rates of 1.47 m^3 biogas/(m^3/d) and 1.00 m^3 CH_4/(m^3/d). The system was able to rapidly adapt to changes in operating conditions. A few days were enough to reach stable conditions when passing from 2.1 to 3.5 Kg VS/(m^3·d) and from 3.5 to 4.5 Kg VS/(m^3·d) with significant increases in biogas production. Likewise, the system rapidly recovered to steady state conditions after moderate temperature shocks.

Typical methane yields ranging from 75 to 223 L CH_4/kg VS were reported for dairy manure with up to 7% TS in various digester configurations (Ogejo and Li, 2010). Lo et al. (1983) reported methane production of 0.50 L CH_4/(L·d) and 0.106 L CH_4/ g VS for screened dairy manure and 0.25 L CH_4/(L·d) and 0.025 L CH_4/g VS for unscreened manure. Hawkes et al. (1984) reported methane yields of 0.119, 0.166 and 0.204 L CH_4/g VS at 5, 10 and 15 days HRT, respectively, on the anaerobic digestion of screened cattle slurry. Dugba and Zhang (1999) obtained a maximum of 0.82 L CH_4/(L·d) when treating screened dairy manure with two-stage (thermophilic-mesophilic) anaerobic sequencing reactor systems. Wen et al. (2007) reported 0.88 L

$CH_4/(L \cdot d)$ for the anaerobic digestion of liquid dairy manure using a sequential CSTR system.

The biogas production rate of the CSTR digester was affected not only by HRT but also especially by the quality of the feed. This quality was related to the VFA content of the SLF. In this work, the feed characteristics were not the same for the different HRTs tested. Mean COD_{VFA} concentrations were 9.2, 6.4, 12.4 and 14.3 for the SLF used as feed at 20, 16.7, 12.5 and 10 days HRTs, respectively. For the shorter HRTs, 12.5 and 10 days HRT, the VFA concentration of the feed was also higher. For this reason, biogas production increased significantly, which explains the higher specific methane production and biogas production found in this work compared with those reported by other authors. In terms of methane yield per litre of feed, from the data in Table 4 and methane content of biogas, it can be deducted that the CSTR system yielded 8.3, 7.8, 9.5 and 10.0 L CH_4/L feed (SLF) at 20, 16.7, 12.5 and 10 days HRT, respectively, under steady state conditions.

3.2.3. Volatile fatty acids in anaerobic effluent

Figure 5 shows the COD_{VFA} concentration values in influents and effluents during the experimental period. With regard to the VFA content in influents, differences were observed amongst feeds. For the shortest HRT, feed showed higher organic loads resulting in VFA contents of the SLF between 12,000 and 14,000 mg/L. Cold winter temperatures allowed for good conservation of manure in the storage tanks during operational periods of 12.5 and 10 days HRT. There was no VFA accumulation in effluents for 20 and 16.7 days HRT. At 12.5 days HRT concentrations between 186 and

423 mg COD_{VFA}/L were observed. On day 120, the drop in the temperature reactor induced an increase in the VFA concentration up to 1764 mg COD_{VFA}/L. Subsequently, when reactor recovered temperature, the VFA concentration decreased to 238 mg COD_{VFA} /L on day 130. At 10 days HRT the concentration of VFA in the effluent rose to values between 621 and 835 mg COD_{VFA}/L. The only VFAs detected in effluents were acetic and propionic acids; acetic was predominant. The effluent pH was maintained close to 8, the VFA accumulation was not critical, and the biogas production and reactor performance were stable. However, the presence of VFA in the effluent indicated that the system was not able to process all the incoming substrate and monitoring of the reactor was stopped.

3.3. Residual methane from digestate

Digestate samples were collected at the exit of the CSTR on days 28, 69, 117 and 174 (Samples: S-20, S-16.7, S-12.5, S-10), corresponding to HRTs of 20, 16.7, 12.5 and 10 days respectively. Figure 6 shows the cumulative and daily specific methane yields for the different digestates. Sample S-10 still had a considerable methane potential (103 mL CH_4/g VS), whereas sample S-12.5 yielded 64 mL CH_4/g VS. That was predictable due to the short HRT in the CSTR reactor and the presence of VFA in the digestate. For samples S-20 and S-16.7, the residual methane was practically negligible (less than 15 mL CH_4/g VS). After sixty days in batch residual methane assays, Samples S-10 and S-12.5 yielded 2.85 and 1.60 L CH_4/L digestate, respectively, whereas the yields recorded from Samples S-20 and S-16.7 were significantly lower, 0.35 and 0.28 L CH_4/L digestate. That is in accordance with Menardo et al. (2010) who reported that high OLR and short HRT promote that digestates still contain considerable amounts of undigested organic matter.

Residual methane recovered from digestates represent 4.2%, 3.6%, 16.8% and 28.4% of the methane yields obtained in the CSTR for HRT of 20, 16.7, 12.5 and 10 days, respectively. Weiland (2003) reported additional methane yields, as high as 15%, for digestate post-methanization. These differences are explained by the different characteristics of the feed in terms of methane potential during the experimental period.

Adding methane yields during CSTR operation and residual methane yields in batch tests would result in the following global methane potentials: 8.7, 8.1, 11.1 and 12.9 L CH_4/L SLF, which corresponds to materials employed during CSTR operation at 20, 16.7, 12.5 and 10 days HRT, respectively. The SLF employed during the last period (10 days THR) yielded 59% more methane than the SLF used at 16.7 HRT, which indicates the importance of good management practices with manure from its generation to the entrance into the anaerobic digester. Uncovered pits combined with heavy rains and manure storage under temperate temperatures of 20ºC leads to lower methane production per mass or volume of SLF. In this case, manure from the same farm resulted in quite different methane yields.

If we use the results obtained in this work to estimate the amount of methane potential in Cantabria from the SLF of manure produced by intensive dairy farming (1,844,391 tons manure per year according to PSE-PROBIOGAS), 29.8 and 19.4 million Nm^3 biogas and methane could be produced per year respectively. These volumes of biogas would represent an electricity production of 67.9 GWh/year in combined heat and power production systems, 2% of total electricity consumed in 2008 in Cantabria.

4. Conclusions

The performance of a 1.5 m^3 volume CSTR digester processing the screened liquid fraction of dairy manure was analysed herein. At HRTs as short as 10 days, the digester showed a stable operation reaching a volumetric biogas production rate close to 1.5 $m^3/(m^3 \cdot d)$. Under these conditions, the digestate yielded an attractive amount of gas, 28.4% of that produced in the CSTR, which implies that the digestate tank should be covered to capture its residual methane yield. At 20 days HRT, a larger reactor size would be required, but since the residual methane yield of digestate was negligible, the storage tank of digested material could remain uncovered without significant gaseous emissions to the atmosphere and methane losses. The potential of biogas production from dairy cattle manure in the region of Cantabria represents a good opportunity. Only the screened liquid fraction could produce the 2% of total electricity consumed in the region.

Acknowledgements

This project was made possible by a contract between the Environment and Education Councils of the Government of Cantabria and the University of Cantabria and was supported by the Environment Council, Project 05-640.02-2174 entitled "Environmental Management of Dairy Cattle Manure in Cantabria". The study presented herein was performed within the framework of the NOVEDAR Consolider CSD2007-00055.

References

Albertson, M.L., Pruden, A., Oliver, R.T., 2006. Enhanced anaerobic digestion of biomass waste for optimized production of renewable energy and solids for compost. Int. Congress Series 1293, 221-229.

APHA, 1998. Standard methods for the examination of water and wastewater, 18^{th} ed. American Public Health Association, Washington, DC, USA.

Atallah, T., Andreux, F., Choné T., Gras, F., 1995. Effect of storage and composting on the properties and degradability of cattle manure. Agric. Ecosys. Environ. 54, 203-213

Chae, K.J., Jang, A., Yim, S.K., Kim, I.S., 2008. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresour. Technol. 99, 1-6.

Boe, K., Angelidaki, I., 2009. Serial CSTR digester configuration for improving biogas production from manure. Water Res. 43, 166-172.

Converse, J.C., Koegel, R.G., Straub, R.J., 1999. Nutrient and solids separation of dairy and swine manure using a screw press separator. ASAE paper nº 99-4050. St. Joseph, MI: ASAE.

Dugba, P.N., Zhang, R., 1999. Treatment of dairy wastewater with two-stage anaerobic sequencing batch reactor systems - thermophilic versus mesophilic operations. Bioresour. Technol. 68, 225-233.

García, H., Rico, C., García, P.A., Rico, J.L., 2008. Flocculants effect in biomass retention in a UASB reactor treating dairy manure. Bioresour. Technol. 99, 6028-6036.

Hartmann, H., Ahring, B.K., 2005. Anaerobic digestion of the organic fraction of municipal solid waste: influence of co-digestion with manure. Water Res., 39, 1543-1552.

Hawkes, F.; Rosser, B.; Hawkes, D.; Statham, M. Mesophilic anaerobic digestion of cattle slurry after passage through a mechanical separator: factors affecting gas yield. Agric. Wastes 1984, 10, 241-256.

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100, 5478-5484.

Kaparaju, P.L.N., Rintala, J.A., 2003. Effects of temperature on post-methanization of digested dairy cow manure in a farm-scale biogas production system. Environ. Technol. 24, 1315-1321.

Kaparaju, P., Buendia, I., Ellegaard, L., Angelidaki, I., 2008. Effects of mixing on methane production during thermophilic anaerobic digestion of manure: Lab-scale and pilot-scale studies. Bioresour. Technol. 99, 4919–4928.

Karim, K., Klasson, K., Hoffman, R., Drescher, S., De Paoli D. Al-Dahhan, M., 2005. Anaerobic digestion of animal waste: effect of mixing, Biores. Technol. 96, 1607-1612.

Liao, P.H., Lo, K.V., Chieng, S.T., 1984. Effect of liquid-solids separation on biogas production from dairy manure. Energy Agric. 3(1), 61-69.

Lo, K.V, Bulley, N.R., Liao, P.H., Whitehead, A.J., 1983. The effect of solids-separation pre-treatment on biogas production from dairy manure. Agric. Wastes 8, 155-165.

Mantovi, P., Fabbri C., Soldano M., Piccinini S., 2010. Effect of solid/liquid separation on raw and digested slurries. Proceedings of the 14th International Ramiran Conference.

Menardo, S., Gioelli, F., Balsari, P., 2011 The methane yield of digestate: Effect of organic loading rate, hydraulic retention time, and plant feeding. Bioresour. Technol. 102, 2348-2351

Møller, H.B., Lund, I., Sommer, S.G., 2000. Solid–liquid separation of livestock slurry: efficiency and cost. Bioresour. Technol. 74, 223-229.

Møller, H.B., Sommer, S.G., Ahring, B.K., 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. Bioresour. Technol. 85, 189–196.

Morris, D.R., Lathwell, D.J., 2004. Anaerobically digested dairy manure as fertilizer for maize in acid and alkaline soils. Commun. Soil Sci. Plant Anal. 35, 1757-1771.

Ogejo, J.A., Li, L., 2010. Enhancing biomethane production from flush dairy manure with turkey processing wastewater. Appl. Energ. 87, 3171–3177.

Pain, B.F., Hepherd, R.Q., Pittman, R.J., 1978. Factors affecting the performance of four slurry separating machines. J. Agric. Eng. Res. 23, 231–242.

Rico, J.L., García, H., Rico, C., Tejero, I., 2007. Characterisation of solid and liquid fractions of dairy manure with regard to their component distribution and methane production. Bioresour. Technol. 98, 971-979.

Weiland, P., 2003. Production and energetic use of biogas from energy crops and wastes in Germany. Appl. Biochem. Biotechnol. 109, 263–274.

Weiland, P., 2006. Biomass digestion in agriculture: a successful pathway for the energy production and waste treatment in Germany. Eng. Life Sci., 6, 302-309.

Wen, Z., Frear, C., Chen, S., 2007. Anaerobic digestion of liquid dairy manure using a sequential continuous-stirred tank reactor system. J. Chem. Technol. Biot. 82, 758-766.

Wu, Z., 2007. Phosphorus and Nitrogen Distribution of Screw Press Separated Dairy Manure with Recovery of Bedding Material. Appl. Eng. Agric. 23, 757-762.

Zhang, R.H., Westerman, P.W., 1997. Solid-liquid separation of animal manure for odor control and nutrient management. Appl. Eng. Agric. 13, 385-393.

Zeeman, G., Sutter, K., Vens, T., Koster, M. Wellinger, A., 1988. Psychrophilic digestion of dairy cattle and pig manure: start-up procedures of batch, fed-batch and CSTR-type digesters. Biol. Wastes 26, 15–31.

Figure Captions

Figure 1- Scheme of the pilot installation.

Figure 2- Removal percentage of VS and COD during CSTR operation. White rhombus represent mean VS removal percentage and black squares represent mean removal percentage of COD for the four HRT tested.

Figure 3- CSTR daily biogas production. In this figure, daily biogas production (black circles) is represented during all the experimental period. The black line represents the HRT during the test.

Figure 4- Biogas methane content during CSTR operation. The methane content of biogas (black circles) is represented during all the experimental period. The black line represents the HRT during the test.

Figure 5- VFA in affluent and effluent during CSTR operation. This figure represents punctual COD_{VFA} concentration during the experimental period for influents (white circles) and effluents (black circles). The black line represents the HRT during the test.

Figure 6- Methane cumulative (1) and daily specific methane yields (2) of digestate samples. Graphic (1) represents methane accumulated at batch tests for digestate samples and graphic (2) the daily specific methane yields for the same tests (White circles - digestate from CSTR at 20 days HRT; black rhombus - digestate from CSTR at 16.7 days HRT; white triangles - digestate from CSTR at 12.5 days HRT; black squares - digestate from CSTR at 10 days HRT).